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Investigation on Stability and Performance of a Free-Piston Stirling Engine

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Abstract

The stable operation of a free-piston Stirling engine will be achieved when both engine configurations and operating conditions are optimum. This paper presents stability and performance investigation of free-piston Stirling engine. Isothermal analysis is considered in the simulation. Dynamic motion of engine pistons such as the displacer and the power piston are both obtained. For engine design, the optimum parameters are given such as engine specifications, engine characteristics and working conditions to yield the maximum efficiency and reliability. The prototype was built and tested. The comparison of both experimental and simulation results are provided and discussed.

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1. Introduction

Global warming affects significantly on the current climate in all areas of the world. Many researchers investigated that the increasing of world temperature results from the rise and excess of CO₂ is the major problem because of green house effect. The main source of CO₂ is come from fossil fuel combustion as in automobile, internal combustion engine(ICE) machine, industrial factories, power plants and etc. Fossil

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fuel, even though, provides such high energy and meets requirement but it also gives CO₂ and pollutions. Alternative and renewable energy, therefore, was used to compensate and reduce excess CO₂ such as biomass and solar energy. Stirling engine, first patented by Robert Stirling in 1816, is a mechanical device that can be used to convert heat from multi-fuels to be useful power without combustion inside the engine and no pollution. Many applications were investigated and integrated with the Stirling engine. Free piston Stirling engine (FPSE) was invented by W. Beale. Modern Stirling engine was developed by using advanced technology materials and manufacturing processes. Consequently, FPSE is a potential and perspective engine for the practical use in both present and future.

Nomenclature

A_d	The cross-section area of the displacer (m ²)
A_p	The cross-section area of the piston (m ²)
A_{dr}	The cross-section area of the displacer rod (m ²)
D_d	The damping coefficient of the displacer motion (N s m ⁻¹)
D_p	The damping coefficient of the piston motion (N s m ⁻¹)
M_d	The mass of the displacer (kg)
M_p	The mass of the piston (kg)
M	The total mass of the gas in the engine (kg)
P	The instantaneous pressure (Pa)
P_{atm}	The atmosphere pressure (Pa)
P_c	The compression volume pressure (Pa)
P_h	The expansion volume pressure (Pa)
P_{max}	The maximum pressure (Pa)
P_{mean}	The mean pressure (Pa)
P_w	The working volume pressure (Pa)
R	The working gas constant (J/ kg K)
t	Time (s)
S_d	The stoke of the displacer (m)
S_p	The stoke of the piston (m)
T_c	The cold volume temperature (K)
T_h	The hot volume temperature (K)
T_r	The mean temperature of the regenerative channel (K)
V_c	The volume of the cold space (m ³)
V_h	The volume of the hot space (m ³)
V_{dc}	The dead volume of the cold space (m ³)
V_{dh}	The dead volume of the hot space (m ³)
X	The dead volume ratio
X_d	The displacement of the displacer (m)
X_p	The displacement of the piston (m)
$\ddot{X}_d$	The acceleration of the displacer (m)
$\ddot{X}_p$	The acceleration of the piston (m)
δ	The calculation parameter
τ	The temperature ratio, T_c/T_h
k	The swept volume ratio, V_c/V_h
α	The phase angle

Wood J G. et al, [1] studied the thermodynamic performance and characterization for three models of current Sun power free-piston Stirling engines: 35 W, 80 W and 1.1 kW. Sun power engines achieve overall efficiencies of greater than 55% of Carnot efficiency.

Rogdakis E.D. et al, [2] presented the thermodynamic investigation for the optimization of stable operation of FPSE. The equations of the angular velocity are solved analytically in terms of mass of the working gas and the displacer–piston phase angle of the machine. Using the criterion of stable engine cyclic steady operation, a mathematically rigorous form is obtained for the main parameters of the engine. The thermodynamic magnitudes are obtained by using the Schmidt analysis (isothermal model).

Kim S Y. et al, [3] proposed the design of an advanced small 35 W- FPSE with integral linear alternator for space power applications. Notable features of the design are high thermal to electric energy conversion efficiencies (exceeding 50 percent of Carnot) and high specific power (~ 100 W/kg).

Boucher J. et al, [4] presented the dynamic behavior of a dual free-piston Stirling engine (DFPSE) coupled with an asynchronous linear alternator. They evaluated the thermo-mechanical conditions for stable operation of the engine. The DFPSE produces a mechanical power of 1 kW and it has a design operating point of 1.4 MPa corresponding to the frequency about 22 Hz. Helium is the working fluid.

Vichaidit N. et al, [5] designed, manufactured and tested the free piston Stirling engine having 46.65 cm³ swept volume. The prototype was operated with temperature in the range of 100 °C – 280 °C at atmospheric pressure. Frequency-stroke characteristics of the engine were measured. The experimental results showed that the maximum output power of 4.69 W was obtained at the hot space and cold space temperature of 163 °C and 40 °C, respectively, and frequency and stroke of 4 Hz and 40 mm, respectively

Kwankaomeng S. et al, [6] presented performance of FPSE with the swept volume of 23 cm³. Engine was unpressurized. Air is used as the working gas. The prototype is heated by alcohol burner and cooled by air. The testing results showed that the engine obtained output power about 0.10 W at 730 rpm of engine speed with the input heat rate of 10.45 W. However, the research is only a preliminary experiment to determine the performance of the engine. This study, therefore, was conducted experimental tests in order to evaluate the appropriate value of crucial parameter for the stable operation of the engine.

2. General principle

2.1. Free-piston Stirling engine configuration

Stirling engine is hot gas engine which include two dynamic parts, displacer and power piston. The gas inside the engine is circulated by the displacer between the hot and cold sections which are called expansion and compression space, respectively, as illustrated in Fig. 1. Figure 1 shows a free piston Stirling engine with a beta type construction. The displacer and the power piston are incorporated in the same cylinder. The displacer moves the working fluid between the hot space and the cold space inside the cylinder through the heater, regenerator and cooler. The power piston is located at the cold or compression space of the cylinder while the displacer is placed between expansion and compression spaces.

Both displacer and power piston are reciprocated linearly in engine cylinder under gas spring or other spring forces.

2.2. Stirling cycle

Stirling cycle as represented in Fig. 2 consists of four processes as following:

Process 1–2: Isothermal compression.

At the beginning of the compression stroke the displacer at BDC held there by its own weight then the power piston is moved down, when it near BDC it compress almost all gas into the displacer cylinder that

make pressure increase from 1 to 2 at constant temperature. The work done on the working fluid indicated by the area under process 1–2

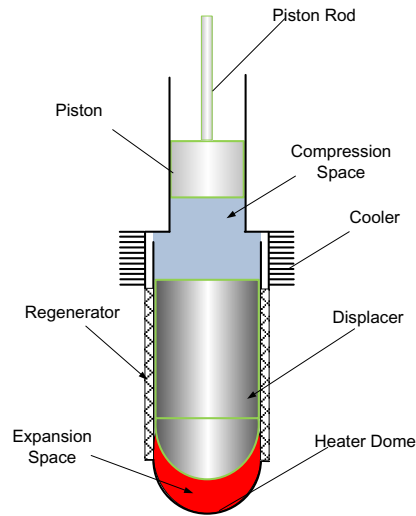


Fig.1. Schematic of FPSE.

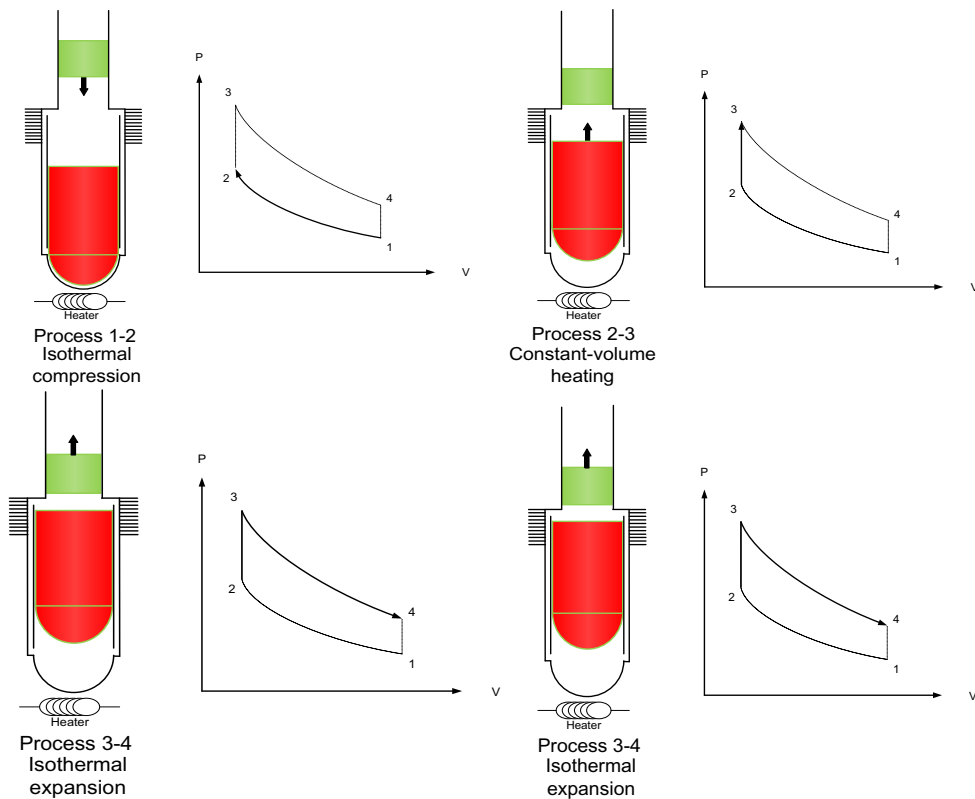


Fig. 2. Stirling Engine Cycle.

Process 2–3: Constant-volume heating

The pressure acting on the displacer is high enough to lift against its own weight, that transfer gas to expansion space, rising the pressure still further so that eventually the displacer is held at TDC. The displacer is pushing the working fluid into the hot space, passing through a regenerator which has stored heat, and already a certain amount is being heated. Heat given up by the regenerator raises the temperature and pressure of the working fluid from 2 to 3 at constant volume, while the power piston remains stationary at its BDC

Process 3–4: Isothermal expansion

After the displacer has pushed all the working fluid into the hot space, with a corresponding increase in pressure to the maximum, it is then kept at rest at its TDC. The working fluid is in the hot space and is expanding to pressure P_4 , while a constant temperature process 3–4 is maintained at the hot space. The power piston is being pushed from BDC to TDC by the increased pressure, and is applying force to create mechanical energy. The work done by the working fluid is indicated by the area under process 3–4

Process 4–1: Constant-volume cooling

After the power piston has reached its TDC and has supplied its energy to the load, it remains stationary and is ready to travel back to BDC under its own weight and the sucking action of the partial vacuum created by the falling of pressure. The displacer is moving from TDC to BDC and transfer working fluid to the cold space where the pressure will fall and a partial vacuum is created, through the regenerator, causing a fall in temperature and pressure of the working fluid from 4 to 1 at constant volume. Heat is transferred from the working fluid to the regenerator [7].

2.3. Schmidt's theory

Schmidt assumptions are typically used in the basic analysis of the Stirling engine operation. The theory provides the harmonic motion of the reciprocating elements and retains the major assumptions of isothermal compression and expansion because of the perfect regenerator assume. It, thus, remains highly idealized, but is certainly more realistic than the ideal Stirling cycle [8].

3. Free-piston Stirling engine (FPSE)

3.1. PFSE prototype

Free piston Stirling engine was invented by W. Beale. The free piston Stirling engines (FPSEs) have no kinematic mechanism coupling the reciprocating elements to each other or to a common rotating shaft. Instead, the elements move entirely in response to the gas or other spring forces acting upon them.

The major advantages of free piston engines include

input and output versatility, quiet operation, zero wear, zero maintenance, long life, ease of interfacing with the electric grid, continuous power operation and potential for high efficiency. The major disadvantage is the difficulty to stabilize the movements of the different elements like piston and displacers [4]. Optimizations of the dynamic behavior of FPSEs are not a simple matter because of the lack of mechanical linkages that are able to fix strokes (displacer and piston) and phase angle for the moving elements (displacer and piston) [2].

The prototype is manufactured as illustrated in Fig. 4. The engine has four crucial components such as displacer, working piston and two of their cylinders. The power piston and its cylinder are made of brass and stainless steel, respectively, for low friction and durability. The aluminium fins around piston cylinder were shaped for air cooling the compressed gas between the displacer and the working piston. The displacer and its cylinder are fabricated from aluminium and stainless steel, respectively.

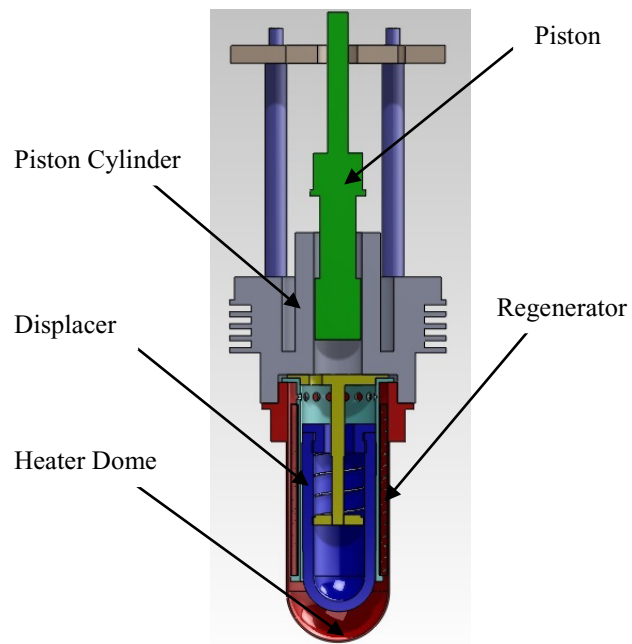


Fig. 3. Schematic of the prototype.



Fig. 4. The FPSE prototype.

3.2. FPSE specification

The specifications of the FPSE are given in table 1.

Table 1. FPSE prototype specification

Free-piston stirling engine data	
Piston length	0.0366 m
Displacer length	0.105 m
Piston diameter	0.027 m
Displacer diameter	0.044 m
Piston stroke	0.03m
Displacer stroke	0.04m
Piston mass	117.0 g
Mass of displacer	224.0 g
Initial gas pressure	101.325 kPa
Working gas	Air
Cooling medium	Air
Heat source	Electric heater

4. Numerical investigation

4.1. General analysis

In order to describe the action of FPSEs, it is useful to assume harmonic motion of the components, which is often nearly true. The mass-spring-damper system is shown in Fig.5.

Newton's second law yields:

$$F + F_{spring} + F_{damping} = M \cdot \ddot{x} \quad (1)$$

The equations of motion of the dynamic elements are

The piston:

$$M_p \ddot{x}_p = (P_c - P_{atm})A_p - D_{pd}(\dot{x}_p + \dot{x}_d) \quad (2)$$

The displacer:

$$M_d \ddot{x}_d = (P_h - P_c)A_d + P_c A_{dr} - kX_d - (D_{dp} + D_h)(\dot{x}_p) \quad (3)$$

The sinusoidal displacement and volume variations are given as in equations (4) to (7) as follows:

$$X_d = \frac{1}{2} S_d \cdot \sin(\omega t) \quad (4)$$

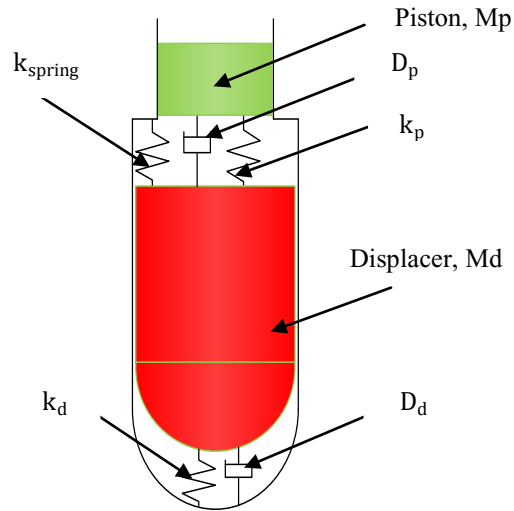


Fig. 5. The spring-damp-mass system.

$$X_p = \frac{1}{2} S_p \cdot (\sin(\omega t - \varphi)) \quad (5)$$

$$V_h = A_d X_d + V_{dh} \quad (6)$$

$$V_c = A_d S_d - V_h + A_p X_p + V_{dh} \quad (7)$$

4.2. Thermodynamic analysis

The approach taken by Schmidt for the analysis follows the isothermal analysis yield the derivation of the pressure and mean pressure given by equation (8) and (9), respectively.

$$P = MR \left(\frac{V_c}{T_c} + \frac{V_{dc}}{T_c} + \frac{V_r}{T_r} + \frac{V_{dh}}{T_h} + \frac{V_h}{T_h} \right)^{-1} \quad (8)$$

$$P_{mean} = P_{max} \left(\frac{1-\delta}{1+\delta} \right)^{1/2} \quad (9)$$

Where

$$\delta = (\tau^2 + k^2 + 2\tau k \cos \alpha)^{1/2} / (\tau + k + 2S) \quad (10)$$

$$S = (2X\tau) / (\tau + 1) \quad (11)$$

$$X = V_{dc} / V_{dh} \quad (12)$$

4.3. Simulation results

Figure 6 shows the displacement of the power piston and displacer. Dynamic motion of the displacer and the power piston are assumed sinusoidal function. The displacer and power piston strokes are 40 and 30 mm, respectively. The displacer leads the piston of 90 degree of phase angle.

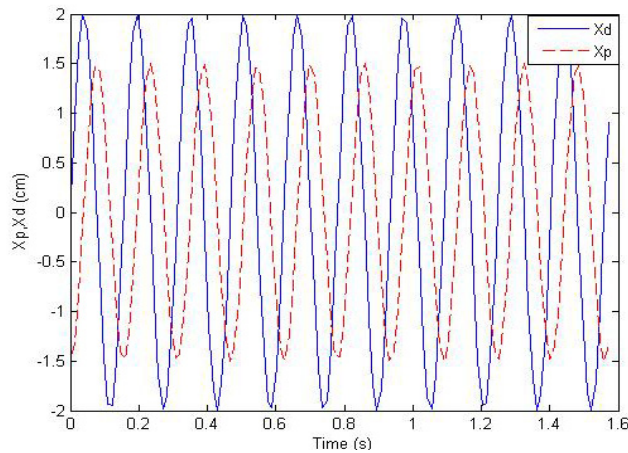


Fig. 6. Piston and displacer stroke at frequency of 6.4 Hz.

The prototype was theoretically investigated using Schmidt's assumptions with initially charging ambient air as the working gas and operated at the hot and cold section temperature of 150 and 40 C, respectively. The PV diagram was obtained as depicted in Fig. 7. The maximum pressure from Schmidt's analysis and experiment result of 146.29 and 134 kPa, respectively.

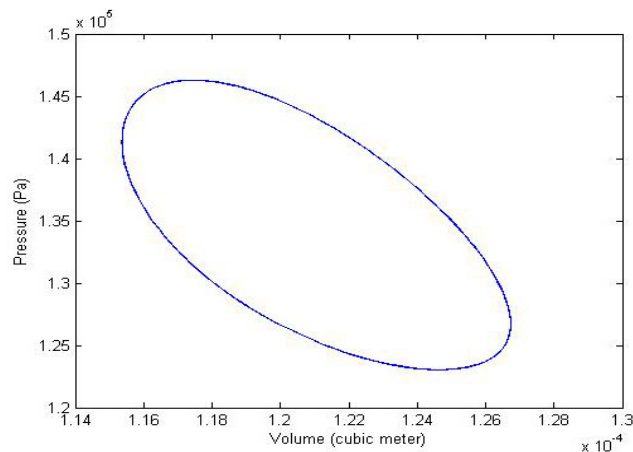


Fig. 7. PV diagram with Schmidt's analysis.

5. Experimental Investigation

5.1. Experimental set up

In order to convert mechanical power to electrical power, the prototype is coupled with linear alternator. Ammeter and voltmeter were used to measure the engine power. Multi-meter was utilized for monitoring the piston reciprocating speed in form of frequency.

The prototype was set up and tested as shown in Fig. 8. Two UT-30C digital multi-meters were used as ammeter and voltmeter. One UN-860C multi-meter was used to measure frequency of the engine.

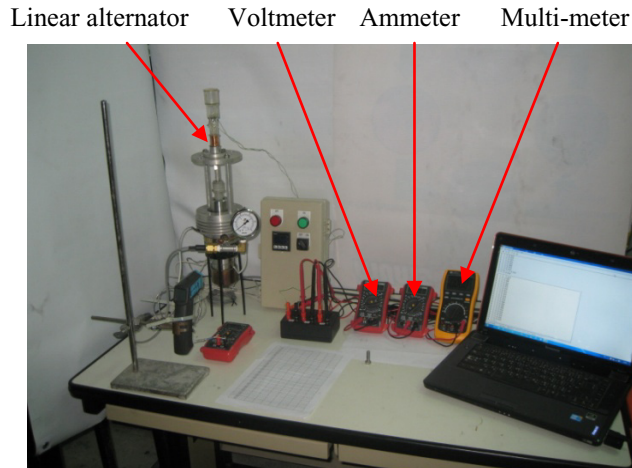


Fig. 8. The FPSE and test equipment.

5.2. Experimental result

The preliminary experiment was conducted in order to find the hot temperature, T_h at the heater section of the engine that can run the engine with the piston mass of 117 g. When the prototype was heated by electric heater of 10 W supply, heat is gained until T_h is high enough to operate the engine. The stable engine operation was obtained at the temperature range of 120-150°C at the heater section.

Figure 9 and 10 show the variation of engine power and engine efficiency with frequency, respectively. When electric heater is supplied 10 W of heat on the engine heater, the power piston was reciprocated randomly with frequency range of 5.9 to 7.0 Hz. Therefore, the sliding motion of the engine piston can be converted to electrical power by linear alternator. Power producing was measured under the variation of piston speed in form of frequency as shown in Fig. 9. Engine power increased when the speed enhanced from 5.9 Hz until the maximum power of 0.68 W was achieved at 6.4 Hz then the power reduced when the piston was moved over 6.4 Hz of frequency.

The relationship of the engine efficiency and engine speed was plotted in Fig. 10. The maximum efficiency of 5.6% at 6.4Hz of frequency was obtained. The efficiency of the engine increased with the enhancing engine speed from 6 to 6.4 Hz while the reduction of efficiency occurred when engine speed more than 6.4 Hz.

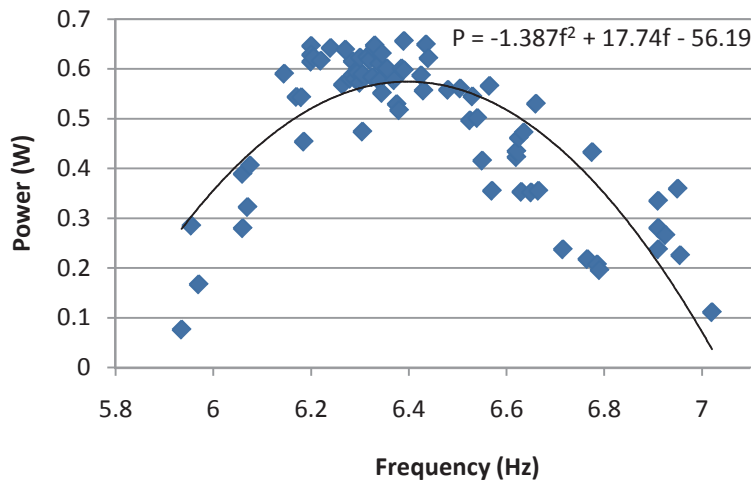


Fig. 9. Power of the engine with frequency.

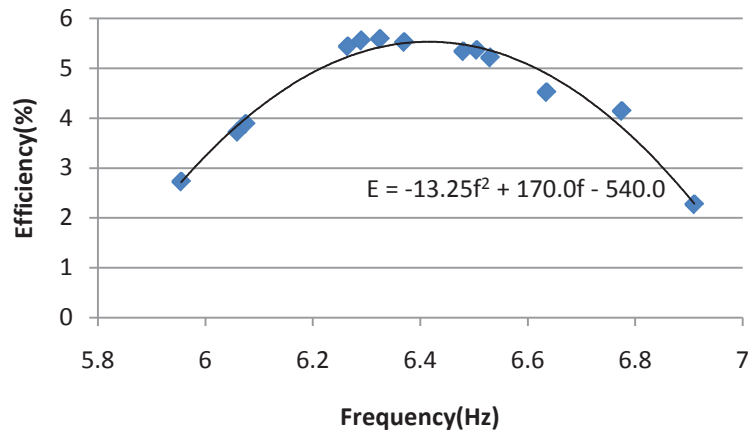


Fig. 10. Efficiency of the engine with frequency.

6. Conclusion

The FPSE model was analyzed dynamic motion of engine pistons and PV diagram with Schmidt's assumptions such as imperfect regenerator, amount of working fluid is constant, isothermal in expansion and compression process and etc. The FPSE prototype was preliminary tested and evaluated engine characteristic and performance. The prototype is heated by electric heater and cooled by air. The engine pressure is initially at 1 bar. The testing results of the FPSE showed that the engine provided maximum output power of 0.68 W at 6.4 Hz of engine frequency with the input heat of 10 W. The stability of engine operation can be obtained at the frequency range of 6.2-6.4 Hz. However, the preliminary tests of the

FPSE prototype were conducted under poor operating conditions such as using atmospheric air as a working gas and air cooling at the cooler.

References

- [1] Wood J. G., Lane N.W.; Advanced 35 W Free-Piston Stirling Engine for Space Power Applications. CP654, Space Technology and Applications International Forum, STAIF 2003.
- [2] Rogdakis E.D., Bormpilas N.A., Koniakos I.K.; A thermodynamic study for the optimization of stable operation of free piston Stirling engines. *Energy Conversion and Management* 45 (2004) 575–593
- [3] Kim S.Y., Huth J., Wood J.G.; Performance Characterization of Sun power Free-Piston Stirling Engines. The 3rd International Energy Conversion Engineering Conference, San Francisco, California. 15-18 August 2005
- [4] Boucher J., Lanzetta, F., Nika, P.; Optimization of a dual free piston Stirling engine. *Applied Thermal Engineering* 27 (2007) 802–811
- [5] Vichaidit N., Aksornpromrat N., Kijswang S.; Design and Construction of Free -Piston Type Stirling Engine, Final year project report, Department of Mechanical Engineering, Siam University. 2009.
- [6] Kwankaomeng S., Silpsakoolsook B., Kaweemong- kolrat T.; Experimental Investigation of a Free-Piston Stirling Engine. The 12th Annual Conference of Thai Society of Agricultural Engineering “International Conference in Agricultural Engineering” Chon-Chan Pattaya Resort, Chonburi, Thailand; 31 March-1 April 2011
- [7] Kongtragool B., Wongwises, S.; A review of solar-powered Stirling engines and low temperature differential Stirling engines. *Renewable and Sustainable Energy Reviews* 7 2003,131–154
- [8] Walker G.; Stirling engines. Oxford: Clarendon Press,1980.